Multiple patterning with process optimization method for maskless DMD-based grayscale lithography

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Multiple Patterning with Process Optimization Method for Maskless DMD-Based Grayscale Lithography

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Abstract

We report a multiple patterning approach utilizing digital-micromirror-device (DMD)-based grayscale lithography, providing a solution to improve fabrication accuracy for entire target three-dimensional structure. Because DMD-based lithography system consists a projection lens system, better resolution can be obtained around focal position comparing to the outer region of depth of focus. Thus, for thick-film resist microstructuring, exposing with multiple focal positions with separate grayscale masks leads to improvement of fabrication accuracy. In order to find the best combination of the multiple focal positions and their grayscale masks, the computational optimization is combined to the multiple patterning approach. Through a several experiments, effectiveness of the proposed approach was successfully demonstrated.

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Keywords: Grayscale lithography, Simulation, Optimization, 3D microfabrication

1. Introduction

Three-dimensional (3D) lithography provides a patterning solution for free-form 3D microstructures in thick-film resist. Usually, 3D lithography is achieved through a gray-tone UV exposure technique in order to control the development rate and, therefore, the final development depth in a positive resist. To date, several types of grayscale lithography for 3D microstructures has been proposed such as grayscale mask lithography using a high-resolution optical photomask [1], moving-mask UV lithography [2] and digital micromirror device (DMD)-based grayscale

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lithography [3]. Recently DMD-based grayscale lithography has been received major attention because DMD can project the grayscale mask pattern directly, instead of relying on a high-resolution optical photomask. Among the numerous process parameters of DMD-based grayscale lithography, the exposure dose pattern (i.e., the grayscale mask pattern, by means of digital bitmap data), the focal position in the resist and the development time most strongly influence the final profile of 3D structure. In order to decide these process parameters, the authors developed the computational process optimization, and the validity and effectiveness were successfully demonstrated using a 20-μm-thick layer of resist [4]. Although previous single patterning approach could achieve higher fabrication accuracy around the optimized focal position locally, further improvement for entire target structure was a remaining challenge. In order to achieve the further fabrication accuracy, this paper reports a multiple patterning with the optimization that is exposing thick-film resist with multiple optimized grayscale masks.

2. Multiple patterning with the process optimization

2.1. Concept

The multiple patterning presented in this paper is a DMD-based lithography technique to exposing a thick-film resist at the two or numerous focal positions with separate grayscale mask patterns. The idea behind this technique is that, in a projection optical lithography, better resolution can be obtained around focal position comparing to the outer region of depth of focus (DOF). Generally, for DMD-based grayscale lithography system, one focal position is set for one exposure process (Fig. 1(a)). As shown in Fig. 2, when the focal position shifts from the bottom ($f = -4$ μm) to the top ($f = -15$ μm), the signed error around the top (position in Fig. 2(b): −15 μm ~ 15 μm) decreased while the error near the bottom increased. So, the simulated resist profile of the cross-sectional shape around focal position exhibits good agreement with the target microstructure. In order to improve the fabrication accuracy for entire target structure, numerous focal positions should be set for separate grayscale mask according to the horizontally divided target structure (Fig. 1(b)). However, separate grayscale masks are not possible to design without a simulation-based approach. Therefore the automated process optimization has been combined to the proposed fabrication technique.

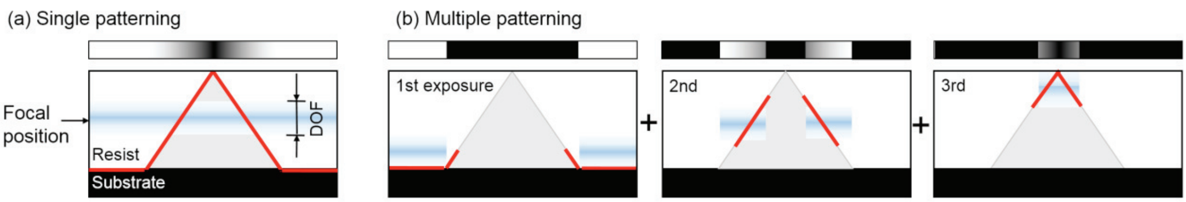


Fig. 1. Conceptual illustrations of the exposure step: (a) the single patterning and (b) the multiple patterning.

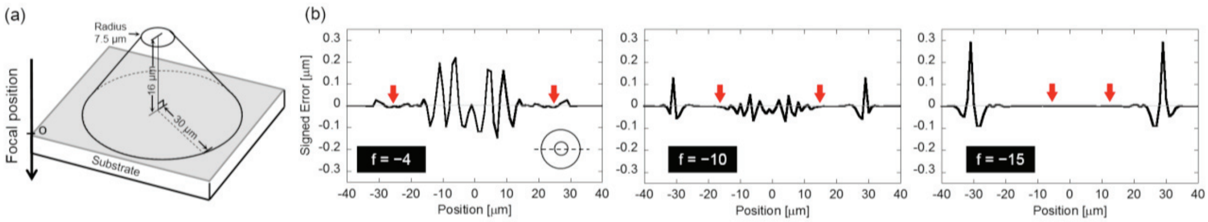


Fig. 2. Effect of the focal position on fabrication accuracy of the single patterning: (a) Target resist structure, (b) error distribution (signed) of simulated structures along the cross section. The focal point of −10 μm is the optimized one for the single patterning approach. The red arrows indicate the resist surface area near the focal positions.

2.2. Optimization method

The optimization method for the multiple patterning consists of optical simulation model of DMD-based grayscale lithography [4], development simulation, and an optimizer based on the steepest descent method [5, 6], using gradient information from sensitivity analysis. The flowchart shown in Fig. 3 summarizes the optimization procedure for the multiple patterning: First, perform the exposure simulation considering effects of the projection system and the development simulation. Next, evaluate the error between the target structure and the simulated structure. Afterwards, perform an adjoint sensitivity analysis to examine how the developed geometry changes when the exposure conditions are altered. This information is used at the optimizer to iteratively update. Finally, the optimization outputs the optimized development time and multiple grayscale masks.

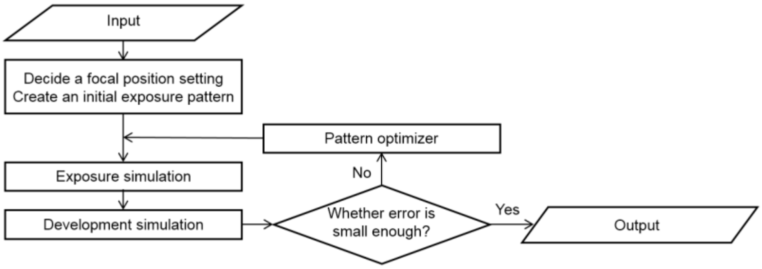


Fig. 3. Flowchart of the optimization procedure.

3. Experiment

Experiments were carried out using a commercially available positive resist. The sample preparation and evaluation were conducted as follows: (1) a 20-µm-thick layer of resist (PMER P-LA900PM, Tokyo Ohka Kogyo Co. Ltd.) was spin-coated on a Si wafer, (2) a pre-bake process was performed on a hotplate, (3) an exposure procedure of the multiple patterning was conducted on a DMD-based grayscale lithography system (DL-1000GS/KCH, NanoSystems Solutions, Inc.), (4) a development process was carried out using the dip method. After a specific development time, the wafer was rinsed in water, and (5) the fabricated structure was observed using a scanning electron microscope (SEM), and the profile was acquired using a 3D laser scanning microscope (VK-X200, Keyence Co.).

4. Results and discussion

Figure 4 shows the relationship between the focal positions and optimized grayscale masks for the multiple patterning. In this experiment, the target structure was divided equally by 1 µm, that is smaller than DOF (3.3 µm) of the employed lithography system. Figure 5 shows the SEM image of the fabricated structure using the optimized process parameters summarized in Fig. 4. Figure 6 compares the fabrication accuracy of the traditional look-up table approach [7], the single patterning [4] and the multiple patterning. The best results of unsigned areal error and signed error of the cross-sectional shape were obtained by the multiple patterning, leading to higher fabrication accuracy with the entire target structure. Therefore the effectiveness of the proposed technique has been demonstrated. However, surface patterns are visible on the fabricated resist structures, which should be improved in the future.

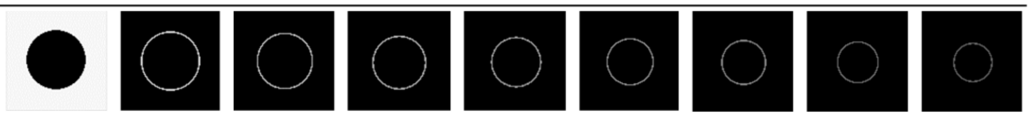
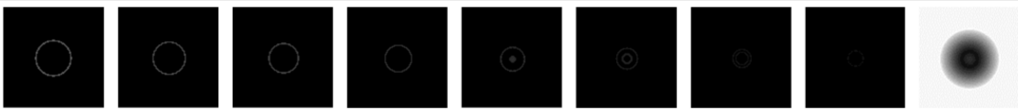
Grayscale mask pattern									
Focal position [µm]	-3	-4	-5	-6	-7	-8	-9	-10	-11
Exposure dose [mJ/cm^2]	561.35	504.12	449.08	411.66	374.24	339.01	308.19	277.37	242.15
Grayscale mask pattern									
Focal position [µm]	-12	-13	-14	-15	-16	-17	-18	-19	Entire pattern
Exposure dose [mJ/cm^2]	209.13	178.31	151.90	123.28	103.47	83.65	59.43	37.42	561.35

Fig. 4. Optimized grayscale mask patterns for each focal position; in this experiment, the resist is exposed with optimized 17 grayscale masks at their focal positions ($f = -4$ µm ~ -19 µm). After the exposure step, the resist sample is developed at the optimized development time of 504 sec.

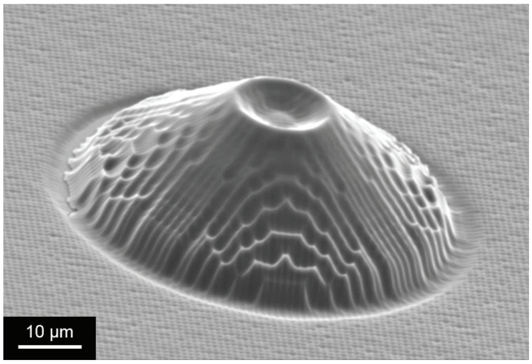


Fig. 5. SEM image of the fabricated resist structure by the multiple patterning.

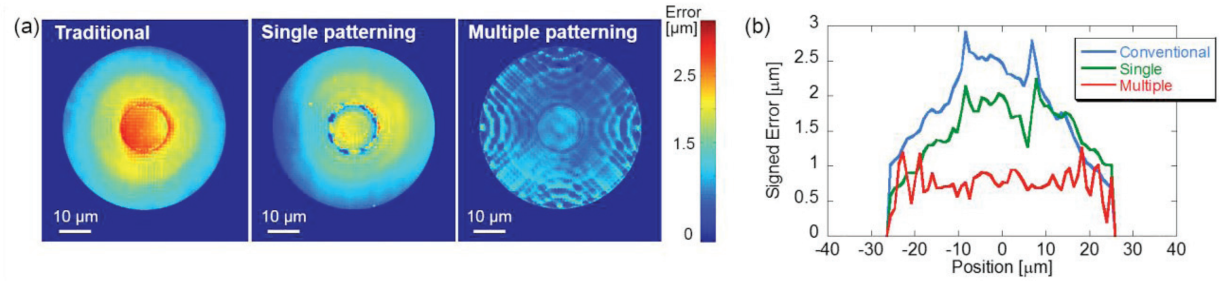


Fig. 6. Comparisons of fabrication accuracy for different three approaches (the traditional look-up table approach, the single patterning and the multiple patterning). (a) Unsigned areal error distribution and (b) signed error at the cross section.

5. Conclusions

We presented a multiple patterning with the process optimization for 3D microfabrication by means of a DMD-based grayscale lithography system. Through several experiments, the effectiveness of the proposed approach has been demonstrated. Consequently, the design time can be significantly reduced, while at the same time, fabrication accuracy is improved.

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